"Experiments, made at Watford, on the Vibrations occasioned by Railway Trains passing through a Tunnel." By Sir James South, LL.D., F.R.S., &c., one of the Visitors of the Royal Observatory of Greenwich. Received June 17, 1863*.

In the year 1846 an attempt was made to obtain the consent of the Lords of the Admiralty to run a railway through Greenwich Park, distant only 860 feet from the Royal Observatory, which would in the opinion of many competent judges have been most injurious to that Establishment. Such consent their Lordships refused; but as I was assured on high authority that this attempt was to be repeated, and that too with the fullest confidence of success on the part of its projectors and supporters, I determined to make experiments which might bear more decisively on the question of railway tremors, as affecting that Observatory, than those previously made by myself and others.

For this purpose it seemed indispensable that the station selected for making them should geologically resemble that of Greenwich, and that the astronomical means employed to detect the existence and determine the intensity of the tremors should be, optically, at least equal to the telescope of the Greenwich Mural Circle.

As much importance was attributed by the advocates of this railway to the supposed power of a tunnel to render the vibrations imperceptible, it was also desirable that *it* should be one of the conditions of these trials.

Having but little more than a popular knowledge of geology, I relied on my old and valued friend the late Mr. Warburton, who had recently been President of the Geological Society, to guide me in the choice of a station; and it was on his authority that I fixed on the Watford Tunnel and its immediate vicinity.

There, under a light gravelly soil of 18 or 20 inches deep, lies a bed of gravel of considerable but variable thickness, sometimes compact, at other times loose, and immediately under it chalk with occasional flints.

The tunnel, of which the bearing is 41° 19′ to N.W. of the meridian, and by my measurement is 1812 yards long, passes principally through chalk; its arch is about 24 feet in diameter, the crown of it being about 21·5 feet above the rails. The thickness of the brickwork is about 18 inches; the mean thickness of the chalk above the crown of the arch about 50 feet, whilst that of the gravel, though subject to great irregularity, may perhaps be regarded as 14 feet. If so, we have outside the tunnel above the horizontal plane of the rails 87 feet of chalk, flint, gravel and soil, constituting an assemblage of which the power of transmitting tremors must be comparatively feeble.

There are five shafts in the tunnel, four of which are circular, 8·5 feet diameter, and one quadrangular, about 26 feet by 34.

* Read June 18, 1863: see Abstract, vol. xii. p. 630.

The tunnel runs under the park of the Earl of Essex; and though I had not the honour of a personal acquaintance with the Noble Earl, nor any introduction to him, yet on learning my objects he transmitted to me by return of post, from Carlsbad, a carte-blanche to erect my observatory wherever I pleased, though it were in the very heart of his choicest game preserves. To him therefore is mainly due whatever benefit may accrue to science or to the Royal Observatory from the experiments recorded in this communication.

The point I selected was 302 yards distant from the centre of the line; and the perpendicular from it on the axis of the tunnel meets that at a point 567 yards from the southern or London end of the tunnel, 1245 yards from the Tring or north end, and 594·5 from the fourth shaft. This is the centre of the Observatory which I erected there: it is of wood, as small as is consistent with the necessary accommodation, both for portability and that it might be less agitated by the wind.

It is quadrangular, 12 feet by 10, and its length is in the meridian; the eaves are 8·5 feet, and the ridge of the roof 10 feet above the floor, this last being 4 inches above the ground, which is nearly level with that over the tunnel. The roof is covered with tarpaulins very well secured, so as not to be torn by a gale of wind. In the south and west sides are four windows, which can be opened or shut at pleasure, to light the Observatory by day, or to see powder or other signals at night. In the roof is no opening; but in its northern side there is one which can be shut as required: it is little larger than what is absolutely necessary to allow the reflected rays from the Pole-star to pass uninterruptedly to the observer's eye through its whole revolution.

At its centre, parallel with its sides and resting on the undisturbed gravel 4 feet below the surface, is a mass of brickwork laid in excellent Roman cement, 8 by 3·5 feet at bottom, 7 by 3·5 at top, its length running east and west. On this stand two piers of similar brickwork, 18 inches by 14, and 46 inches higher than the floor: they are capped by two Portland stones of similar horizontal section 8 inches thick. In the interior faces of these stones are firmly fixed the Y-plates, which carry the Ys on which the instrument's pivots rest.

Eighteen inches north of the brick massive, but in the same plane with its base, is the centre of the base of another pier, brought up also in Roman cement, 24 inches from N. to S., 18 from E. to W.; and it rises 12 inches above the floor. The upper surface is perfectly horizontal, and serves to support a vessel which contains mercury. Both this pier and the massives are insulated from the floor, and touch the ground only at their bases. The mercury-vessel was 18 inches by $4\frac{3}{4}$, with its length in the meridian.

The transit-instrument of the Campden Hill Observatory is far too precious to be exposed to the risks of such an expedition; I therefore had one constructed which might be considered an excellent substitute. The object-glass (which under favourable circumstances will bear a power of 1000) is 87 inches focus and 4·75 aperture. The transverse axis is 31 inches; and

the Y has sufficient azimuthal motion to enable me to follow the Pole-star in its whole course, so that at any hour (if clear) I could have the reflected image of the star in the mercurial vessel ready to testify against the tremors caused by a train.

Supported by timber passing into the ground, but unconnected with the floor and convenient to a writing-desk which occupies the S.E. angle of the building, stands a journeyman clock. It is set by my excellent gold pocket-chronometer, Molyneux No. 963, and rarely deviates from that more than one- or two-tenths of a second in three or four hours. The clock of the Watford Station was compared with the chronometer, going and generally returning, for the purpose of identifying particular trains.

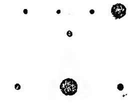
These details will, I hope, suffice to prove that every precaution was taken to obtain accurate results, and that those which I did obtain may be fairly considered as identical with what would have been found in a first-class observatory under the same circumstances of locality and traffic.

I was at my post to commence observations on December 22nd, 1846; but that and the three following nights were starless. The 26th was fine, but, owing to the irregularity of the trains, and the want of well-organized signals, I could only satisfy myself that all was in good working order, and that the trains caused great disturbance. For thirteen following nights I was at my post, but in vain; all was dark, with the thermometer from 22° to 31°.

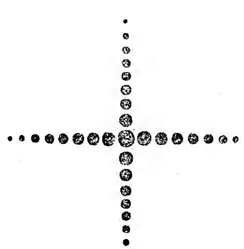
On January 11th, 1847, it cleared, and I observed seven trains with decisive results, being able to *announce* their presence before it was known to my assistants, who were on the watch outside the observatory.

The Pole-star's image as reflected from the mercurial surface, when no train was near, appeared

As a very small, perfectly steady disk, thus— . . . .  (1.)

which as the train approached broke up into a quintuple, thus— . . . .  (2.)

As the disturbance increased, the form became linear at right angles to the length of the mercury-vessel, thus— . . .  (3.)

When the train was considerably advanced in the tunnel, a cross formed, thus— .  (4.)

And when near the perpendicular from the observatory, three parallel lines of disks appeared, thus— . . . .  (5.)

still parallel to No. 3. As the tremors became more distant, these transformations of the image take place in a reverse order, until the star resumes its original disk-like form.

These results were strongly conspicuous even in a fully illuminated field, and equally so whether the magnifying power was 60, 200, or 750. The phenomena are very striking, from the contrast between the smaller images, which are blue, while the larger ones are reddish, and from the sudden way in which they break out.

The nights of the 13th and 14th were fine, and so thoroughly confirmed my previous observations that I felt it my duty to lose no time in informing the late Lord Auckland, then First Lord of the Admiralty, of the preceding details and of my conclusions from them, that a tunnel did not prevent great tremors from being propagated from it when a train was traversing it, certainly to the distance of 643 yards, and probably much further.

The impression which these facts made on his Lordship he expressed in the following letter.

Copy of a Letter from the Earl of Auckland to Sir James South.

"Admiralty, January 26th, 1847.

"SIR,—I have to return you many thanks for the very interesting report which you sent to me of your experiments upon the distance to which the vibration caused by steam-carriages within a tunnel extend; and I cannot but admire the enterprise and ability with which these experiments were conducted. They would be quite conclusive if the question of carrying a tunnel through Greenwich Park were again to be agitated.

"I am, very faithfully yours,

"*To Sir James South, &c. &c.*" "AUCKLAND."

The reserve with which I spoke of that further distance arose from the circumstance that I was not in possession of the exact measurements of the tunnel and the position of its shafts. I had twice applied for them in vain to the railway authorities, and was obliged at last to execute the measures myself*. This consumed some time, and the observations were not completely resumed till February 24, 1847.

The process was this. About 600 yards before the entrance of the tunnel a rocket was fired as a signal for attention. At the instant that the engine passed the south end of the tunnel, one of Lord Essex's game-keepers fired one barrel of his gun, and the other about a second after, which was necessary to distinguish this from the shots of poachers, who were often at

* This delay was not occasioned by any want of courtesy on the part of the Directors or other officers; from whom, especially from Mr. Creed, their Secretary, I received the heartiest cooperation. He not only directed all the officers along the line to aid as far as possible my investigations, but pressed on me free passes for myself and my assistants. I was also indebted to Captain Bruyeres for the character of the trains, and to Mr. Stubbs, the Superintendent of the Watford Station, for the zeal with which he followed out the Secretary's instructions at much personal inconvenience.

work around me. Similar shots were fired when the engine was at the centre of the 4th shaft (which could be seen from above). The times of these signals were taken by an assistant. During this time I was at the telescope, and noticed the second when any peculiar phase of disturbance appeared.

The computation of the distance of the engine from the eye at a given time is very simple. From the known distance of the south end of the tunnel and the 4th shaft from the eye, we know the times taken by the sound of the gun to reach the observatory. The temperature was during the whole series so near 32° that the velocity of sound for that temperature, 363·13 yards, may be used without sensible error. The effect of wind must also have been insensible. Hence the signal from the south entrance was $1^{s}\cdot77$ too late, that from the shaft $1^{s}\cdot84$.

Correcting the times and dividing by their difference the distance of the shaft from the entrance, 1162 yards, we have the velocity of the train (which, however, I have given in miles per hour, as affording a more familiar measure of the disturbing power). Then the difference of the time of phase and corrected time of entrance gives the place of the engine on the line, and the perpendicular is given.

In the following record of the observations, the first column contains the number, the second the times, the third the facts observed, and the fourth gives the distance, then follow occasional remarks. In the disturbances, I specially recorded as most definite the cross (4), and the arrangement of bars of parallel stars (5). The slighter disturbances which precede or follow the former were seldom entered, though quite sensible.

1847, February 24.—I.

No.	Time.	Observations.	Yards.	Remarks.
	h m s			
1	7 18 43	Cross very distinct	845	Velocity 11·00, miles an hour; weight of train 77·5 tons; twelve carriages.
	7 19 21	Shaft gun.		
	7 22 57	South gun.		
2	7 23 8	Lost sight of cross	704	

II.

3	7 34 0	Cross	699	Velocity 16·6 miles; train 69·5 tons, 231 feet long; ten carriages. Thermometer 24°.
	34 8	Shaft gun.		
	36 31	South gun.		
4	36 48	Lost sight of cross......	780	

III.

5	7 44 40	Cross; star very faint...	680	Velocity 13·8 miles. Star invisible to the naked eye. Train 58·5 tons; engine 14·5 tons; length 185 feet.
	44 44	Shaft gun.		
	47 38	South gun.		
6	7 47 42	Lost cross	678	

1847, February 24.—IV.

No.	Time.	Observations.	Yards.	Remarks.
	h m s			
	7 59 6	Shaft gun.		Velocity 11·4 miles; train 89·5 tons; engine 18 ditto; length 308 feet. Wind E. Therm. 24°.
	8 2 30	Star became visible.		
	8 2 34	South gun; star bright.		
7	8 3 10	Cross disappeared	834·5	

1847, February 27.—I.

	7 28 0	Shaft gun.		Velocity 15·4 miles; train 54 tons; engine 14·5 tons; length of train 172 feet.
	29 7	Cross first seen, but star very faint.		
	30 34	South gun.		
8	7 30 44	Cross lost; star very faint....................	722	

II.

9	7 44 43	Cross seen	736	Velocity 25·6 miles; train 49·5 tons; engine 14·5 tons; length of train 150 feet.
	7 44 51	Shaft gun.		
10	45 8	Cross very strong	470	
11	45 27	Line very strong	326	
	46 24	South gun.		
12	46 46	Cross lost	915	

III.

13	7 56 21	Cross seen	706	Velocity 17·6 miles; train 270·5 tons; two engines 29·5 tons; length of train 663 feet; 37 carriages.
	56 31	South gun.		
14	57 45	Cross very strong	314	
	58 46	Shaft gun.		
15	58 53	Cross lost	736	

IV.

16	8 3 36	Cross very strong	736	Velocity 31·7 miles; train 112 tons; engine 21 tons; length of train 394 feet; carriages 17. Wind N.E. Thermometer 26°.
	3 44	Shaft gun.		
17	4 6	Cross very fine	377	
18	4 14	Triple line, upper and lower stars blue	319	
	4 59	South gun.		
19	5 28	Cross lost	1086	

V.

20	8 10 56	Cross seen	727	Velocity 18·7 miles; train 51·5 tons; engine 12·5 tons; length of train 187 feet. A train of empty cattle-waggons.
	11 8	South gun.		
21	11 56	Triple line strong	322	
	13 15	Shaft gun.		
		Cross lost from cloud...	lost	

1847, March 11.—I.

No.	Time.	Observations.	Yards.	Remarks.
	h m s			
22	7 18 44	Cross very distinct......	802	Velocity 17·7; train 147·5 tons; engine 12·5 tons; length of train 355 feet.
	19 6	South gun.		
	21 20	Shaft gun, cloud.		

II.

	8 25 3	Shaft gun, cloud.		Velocity 33·0 miles; train 122 tons; engine 21 tons; length of train 416 feet. Cross so strong, but for the cloud it might have been seen 15 or even more seconds longer.
	26 15	South gun, cloud cleared		
23	26 32	Cross lost by cloud......	921	

1847, March 12.—I.

24	6 56 22	Cross very distinct......	822	Velocity 28·33 miles; train 68 tons; engine 15 tons; length of train 231 feet; many carriages but mostly empty, many wheels and axles; agitation excessive. Seemed to keep time with the jolts of the train.
	56 38	South gun.		
25	56 52	Cross very strong	461	
26	57 16	Star tossed about 3 or 4 of its diameters	302·4	
	58 2	Shaft gun.		
27	58 8	Cross lost	766	

II.

28	7 13 15	Cross plain	811	Velocity 35·5 miles; train 59·5 tons; engine 15 tons; length of train 192 feet. Train does not stop at Watford.
	13 26	Shaft gun.		
29	13 44	Cross very strong	392	
30	13 56	Triple line very strong .	305	
31	14 20	Cross very strong	480	
	14 33	South gun.		
32	14 58	Cross lost	1074	

III.

33	7 57 16	Image much agitated...	1077	Velocity 30·9 miles; train's weight 124 tons; two engines 21 tons and 14 tons; length of train 375 feet. Wind N., very weak. Thermometer 31°·5.
34	57 30	Cross	877	
	57 47	Shaft gun.		
35	58 0	Cross very strong	478	
36	58 10	Parallel lines (5) very strong	374	
37	58 16	(5) still stronger.........	329	
38	58 25	(5) ten lines, quite cover field of telescope......	302	
39	58 45	Cross very strong	431	
	59 4	South gun.		
40	59 14	Cross strong	803	
41	59 31	Cross lost	1045	

1847, March 12.—IV.

No.	Time.	Observations.	Yards.	Remarks.
	h m s			
42	8 40 11	Cross	855	Velocity 37·7 miles; train 50 tons; engine 14·5 tons; train's length 152 feet.
	40 24	Shaft gun.		
43	40 38	Cross very strong	428	
44	40 54	Parallel lines; image trembles	302	The image trembled very much during the whole time of passage through the field.
45	41 10	Strong lines	416	
	41 27	South gun.		
46	41 48	Cross lost	1031	

1847, March 15.—I.

No.	Time.	Observations.	Yards.	Remarks.
47	7 21 14	Cross	1176	Velocity 20·5 miles; train 125·5 tons; engine 22 tons; length of train 409 feet; 18 carriages.
48	22 6	Cross strong	686	
	22 10	Shaft gun.		
49	22 37	Line brilliant; changed suddenly to	430	
50	22 50	Parallel lines (5)	349	
51	23 5	(5) very strong	303	
52	23 15	(5) still strong	311	
53	23 22	Cross very strong	335	
54	24 6	South gun; cross very strong.		
55	24 51	Cross still seen	1078	

II.

No.	Time.	Observations.	Yards.	Remarks.
56	7 25 55	Cross	775	Velocity 22·6 miles; train 209·5 tons; length of train 172 feet; slow goods train.
	26 10	South gun.		
57	27 1	Parallel lines very strong	303	
58	27 10	Do. do. very beautiful...	324	
	27 55	Shaft gun.		
59	28 18	Cross lost	922	

III.

No.	Time.	Observations.	Yards.	Remarks.
60	7 31 19	Cross	1032	Velocity 21·6 miles; train 91·5 tons; engine 14·5 tons; train's length 319 feet.
61	31 52	Cross very strong	706	
	31 58	Shaft gun.		
62	32 30	Single line very strong .	384	
63	32 32	Changed to (5) parallel lines....................	371·5	
64	32 48	(5) very strong	308	
	33 48	South gun.		
65	34 22	Cross lost	992	

IV.

No.	Time.	Observations.	Yards.	Remarks.
66	7 43 37	Cross	786	Velocity 14·8 miles; train 49·5 tons; engine 14·5 tons; train's length 150 feet; six carriages.
67	43 44	Cross strong	740	
	43 57	Shaft gun.		
68	44 22	Line strong..............	502	
69	45 0	Cross very strong	328	
70	45 18	Trace of (5) parallel lines	302	
71	45 37	Line very strong.........	336	
72	45 52	Cross strong	391	
	46 38	South gun.		[leaving the tunnel.
73	46 42	Cross lost	679	I never saw it cease so soon after

1847, March 15.—V.

No.	Time.	Observations.	Yards.	Remarks.
	h m s			
74	8 10 16	Cross	1029	Velocity 33·0 miles; train 106 tons; engine 21 tons; train's length 364 feet.
75	10 35	Cross very strong	741	
	10 42	Shaft gun.		
76	10 52	Line very strong.........	504	
77	11 16	(5) brilliant...............	303	
	11 54	South gun, cross very strong.		
78	12 16	Cross lost	997	

VI.

79	8 25 57	Cross	854	Velocity 15·9 miles. This train could not be identified.
	26 25	Shaft gun.		
80	28 12	Cross very strong	394	
	28 54	South gun.		
81	29 12	Cross lost	782	

VII.

82	8 41 29	Cross	926	Velocity 23·7 miles. Newcastle Express.
	41 55	Shaft gun.		
83	42 21	(5) parallel bars	406	
	43 35	South gun.		
84	44 2	Cross lost	950	

1847, March 16.—I.

85	6 44 49	Cross	1157	Velocity 34 miles; train 75 tons; engine 15 tons; length of train 282 feet.
	45 21	Shaft gun.		
86	46 8	Cross very strong	393	
	46 28	South gun; cross very strong.		
87	46 58	Cross last seen	1157	

II.

88	6 54 14	Cross	935	Velocity 24·8 miles; train 67 tons; engine 14 tons; length of train 231 feet.
	54 42	South gun.		
89	55 34	(5) parallel lines.........	314	
	56 18	Shaft gun.		
90	56 42	Lost cross, but cart within hearing	959	

III.

91	6 58 18	Cross	915	Velocity 11·4 miles; train 322 tons; engine 14 tons; train's length 857 feet. A heavy goods train.
	59 9	Shaft gun.		
92	7 0 11	Line very strong.........	382	
93	0 20	(5) very strong	352	
94	0 30	(5) magnificent	328	
95	0 40	Cross very strong	308	
96	0 55	Cross double very beautiful.	309	
	2 36	South gun; cross very strong.		
97	4 4	Cross lost	1110	

1847, March 16.—IV.

No.	Time.	Observations.	Yards.	Remarks.
	h m s			
98	7 8 5	Cross	870	Velocity 21·9 miles.
	8 30	South gun.		
	10 18	Shaft gun.		
99	10 38	Lost cross	878	

V.

100	7 18 32	Cross	1038	Velocity 25·7 miles; weight of train 69·5 tons; engine 14·5 tons; train's length 194 feet.
	19 5	Shaft gun.		
	20 37	South gun.		
101	21 5	Lost cross	988	

VI.

102	7 42 2	Cross	824	Velocity 35·8 miles; train 53·5 tons; engine 14·5 tons; train's length 168 feet.
	42 14	Shaft gun.		
103	42 43	(5)	305	
	43 20	South gun.		
104	43 45	Lost cross	1079	

VII.

105	8 31 42	Cross	846	Velocity 36·9 miles; train 98·5 tons; engine 21 tons; length of train 322 feet. Wind S.E.; fresh.
	31 55	Shaft gun.		
106	32 9	(5)	428	
	32 59	South gun.		
107	33 22	Lost cross	1058	

VIII.

108	8 43 48	Cross very faint	668	Velocity 20·1 miles; train 55·75 tons; engine 23·75 tons; train's length 146 feet. Tremors unusually small.
	43 50	Shaft gun.		
	45 48	South gun.		
109	46 8	Lost the cross...........	821	

1847, March 17.—I.

110	6 42 45	Cross	1055	Velocity 33·9 miles; train 104 tons; engine 19 tons; length of train 362 feet.
	43 12	Shaft gun.		
111	43 40	(5) beautiful	318	
112	43 55	(5) ditto	337	
	44 22	South gun; cross very strong.		
113	44 54	Cross lost	1166	

II.

114	6 55 26	Cross	1076	Velocity 28·7 miles; train 70 tons; engine 12 tons; train's length 247; feet. Wind S.E.; scarcely sensible; image very unsteady.
	56 1	South gun.		
115	56 37	Line of stars very beautiful.	304	
116	56 46	(5)	315	
	57 24	Shaft gun.		
117	57 35	Cross still very strong...	832	
118	57 47	Cross lost	1004	

1847, March 17.—III.

No.	Time.	Observations.	Yards.	Remarks.
	h m s			
119	7 10 23	Cross	828	Velocity 22·9 miles; train 74·5 tons; engine 12·5; train's length 171 feet.
	10 43	South gun.		
120	11 32	Cross strong	302	
121	11 45	Line strong	336	
	12 27	Shaft gun.		
122	12 47	Cross lost.................	892	

1847, March 18.—I.

No.	Time.	Observations.	Yards.	Remarks.
123	6 18 12	Cross well seen	961	Velocity 27·3 miles; train's weight 87 tons; engine 15 tons; length of train 345 feet.
	18 38	South gun		
124	19 25	(5) strong.	314	
125	20 3	Cross strong	666	
	20 5	Shaft gun.		
126	20 20	Cross still strong.........	875	
127	20 26	Cross lost	950	The image oscillating in every direction.

II.

No.	Time.	Observations.	Yards.	Remarks.
128	6 38 32	Cross strong	902	Velocity 30·4 miles; train 78 tons; engine 19 tons; length of train 246 feet.
	38 51	Shaft gun.		
129	39 20	(5) very strong	331	
	40 9	South gun.		
130	40 11	Strong cross	692	
131	40 24	Cross lost	870	

III.

No.	Time.	Observations.	Yards.	Remarks.
132	6 55 11	Cross	992	Velocity 25·6 miles; train 63 tons; engine 14 tons; train's length 212 feet.
133	55 32	Line strong...............	746	
	55 43	South gun.		
134	56 22	Cross very strong	307	
135	56 33	(5) beautiful	313	
	57 16	Shaft gun.		
136	57 43	Cross lost	1003	

IV.

No.	Time.	Observations.	Yards.	Remarks.
137	7 14 12	Cross strong	824	Velocity 31·6 miles; train 72·5 tons; engine 14·5 tons; train's length 254 feet.
	14 25	Shaft gun.		
138	15 0	(5) beautiful	303	
139	15 12	(5) still fine..............	343	
140	15 26	Cross strong	484	
	15 40	South gun.		
141	16 7	Cross lost	1057	

V.

No.	Time.	Observations.	Yards.	Remarks.
142	7 21 59	Cross	705	Velocity 22·9 miles; a light goods train.
	22 7	South gun.		
143	22 45	Cross strong	326	
	23 51	Shaft gun.		
144	24 5	Cross lost	830	

1847, March 18.—VI.

No.	Time.	Observations.	Yards.	Remarks.
	h m s			
145	7 36 54	Cross	888	Velocity 18·2 miles; train's weight 84 tons; engine 16 tons; train's length 187 feet. All the images inosculated during the train's passage through the tunnel; yet when it was gone the star was perfectly steady. Wolverton goods train.
	37 26	South gun.		
146	38 20	Cross strong	311	
147	38 30	All confusion	303	
148	38 40	Line very strong.........	320	
	39 37	Shaft gun.		
149	40 3	Cross lost...................	895	

VII.

150	7 41 0	Cross	896	Velocity 29·7 miles; train's weight 62·5 tons; engine 14·5 tons; train's length 204 feet. As in last the images inosculated; even the lines of (5) ran into each other. Peterborough light train.
151	41 13	Cross strong	721	
	41 19	Shaft gun.		
152	41 43	(5)	373	
153	42 0	(5) strong	303	
	42 39	South gun.		
154	43 14	Cross lost...................	1141	

VIII.

155	7 59 5	Cross	1111	Velocity 40·2 miles; train 128 tons; engine 19 tons.; length of train 458 feet.
156	59 25	Cross very strong	740	
	59 31	Shaft gun.		
157	8 0 10	(5)	367	
	0 30	South gun.		
158	0 54	Cross lost	1115	

IX.

159	8 38 36	Cross	818	Velocity 41·62 miles; train 61·25 tons; engine 23·75 tons; length of train 144 feet.
	38 46	Shaft gun.		
160	39 0	Cross very strong	406	
161	39 10	(5)	310	
162	39 18	Cross	481	
	39 43	South gun.		
163	40 3	Cross lost	1076	

1847, March 19.—I.

164	6 39 55	Cross seen	858	Velocity 37·9 miles; train 92·75 tons.; engine 23·75 tons; train's length 284 feet.
	40 8	Shaft gun.		
165	40 10	Line very distinct	606	
166	40 25	Cross extremely bright..	390	
	41 0	South gun.		
167	41 37	Cross lost	1128	Observed by the Marquis of Blandford.

1847, March 19.—II.

No.	Time.	Observations.	Yards.	Remarks.
	h m s			
168	6 56 52	Cross	919	Velocity 32·8 miles; train 67 tons; engine 14 tons; train's length 231 feet.
	57 12·5	South gun.		
169	57 30	Cross very bright	397	
170	57 49	(5) very distinct	306	
	58 25	Shaft gun.		
171	58 44	Cross lost	978	Observed by the Marquis of Blandford.

III.

No.	Time.	Observations.	Yards.	Remarks.
172	7 15 20	Cross	697	Velocity 32·1 miles; train 68·5 tons; engine 14 tons; train's length 234 feet.
	15 24	Shaft gun.		
173	15 45	Cross still distinct	383	
174	15 55	(5) slightly	313	
	16 38	South gun.		
175	16 46	Cross lost	781	Observed by Lord Alfred Churchill.

IV.

No.	Time.	Observations.	Yards.	Remarks.
176	7 24 40	Cross	1042	Velocity 24·0 miles; train 98·5 tons; engine 12·5 tons; train's length 156 feet. This night very unfavourable. Many observations lost from clouds, and the stars when seen often faint.
177	24 57	Cross very strong	848·5	
	25 18	South gun.		
178	26 5	Cross extremely strong..	302	
179	26 10	(5)	309	
	26 57	Shaft gun.		
180	27 26	Cross lost	1005	

1847, March 22.—I.

No.	Time.	Observations.	Yards.	Remarks.
181	7 22 12	Cross	759	Velocity 23·6 miles; train 86·5 tons; engine 12·5 tons; train's length 203 feet.
	22 24	South gun.		
182	23 22	Cross strong	323	
	24 5	Shaft gun.		
183	24 33	Cross lost	964	

II.

No.	Time.	Observations.	Yards.	Remarks.
184	7 38 32	Cross	1025	Velocity 20·7 miles; train 68 tons; engine 14·5 tons; train's length 233 feet.
185	39 10	Cross strong	668	
	39 12	Shaft gun.		
186	40 12	(5)	304	
	41 7	South gun.		
187	41 36	Cross lost	950	

III.

No.	Time.	Observations.	Yards.	Remarks.
188	7 58 20	Cross	827	Velocity 31·4 miles; train 88 tons; engine 21 tons; length of train 288 feet.
	58 33	Shaft gun.		
189	59 4	(5) beautiful	312	
	59 47	South gun.		
190	60 8	Cross lost	972	

1847, March 29.—I.

No.	Time.	Observations.	Yards.	Remarks.
	h m s			
191	6 54 58	Cross	837	Velocity 33·1 miles; train 108 tons; two engines, 15 tons and 13 tons; train's length 334 feet.
	55 13	South gun; cross very strong.		
192	55 42	Cross extremely strong..	310	
193	56 0	All lost in a flare	374	
	56 25	Shaft gun.		
194	56 49	Cross lost	1057	

II.

No.	Time.	Observations.	Yards.	Remarks.
195	7 36 0	Cross	849	Velocity 33·4 miles; train 67·5 tons; engine 14·5 tons; train's length 226 feet. At 36^m 45^s the stars lost shape and were inosculated with each other.
	36 14	Shaft gun.		
196	36 40	Cross very strong	333	
	37 25	South gun.		
197	37 43	Cross lost	940	

III.

No.	Time.	Observations.	Yards.	Remarks.
	7 47 43	Shaft gun.		Velocity 20·8 miles; train 48 tons; engine 13 tons; train's length 150 feet. It was stopped by the police at the entrance of the tunnel, and went slowly through it—"crawling," in the words of the signal-man.
198	48 10	Cross first seen	426	
199	48 41	Cross strong	302	
	49 37	South gun.		
200	49 39	Cross lost	677	

IV.

No.	Time.	Observations.	Yards.	Remarks.
201	8 4 6	Cross	698	Velocity 33·4 miles; train 92·5 tons; engine 15 tons; train's length 328 feet.
	4 10	Shaft gun.		
202	4 45	Cross strong	302	
	5 21	South gun.		
203	5 44	Cross lost	1018	

V.

No.	Time.	Observations.	Yards.	Remarks.
204	8 33 12	Cross	774	Velocity 39·5 miles; train 55·5 tons; engine 21 tons; train's length 144 feet. The night unfavourable from clouds.
	33 20	Shaft gun.		
	34 20	South gun.		
205	34 37	Cross lost	978	

1847, March 30.—I.

No.	Time.	Observations.	Yards.	Remarks.
206	6 49 26	Cross	771	Velocity 29·0 miles; train 122 tons; engine 18 tons; train's length 404 feet. Observed by the late Professor James, McCullagh, of Trinity College, Dublin.
	49 36	Shaft gun.		
207	50 10	(5) two faint parallel lines	314	
208	50 15	Stars entirely confused..	302	
	50 58	South gun.		
209	51 16	Cross lost	899	

1847, March 30.—II.

No.	Time.	Observations.	Yards.	Remarks.
	h m s			
210	6 57 57	Cross	940	Velocity 38·4 miles; train 89·5 tons; engine 19 tons; length of train 293 feet.
211	58 10	Cross strong	714	
	58 16	South gun.		
212	58 40	(5) but confused.........	313	
	59 18	Shaft gun.		
213	59 36	Cross lost	1014	Observed by Prof. James McCullagh.

III.

214	7 2 2	Cross	798	Velocity 29·0 miles.; a pilot engine.
	2 14	Shaft gun.		
215	3 36	South gun.		
		Star which had been faint was now totally clouded.		Observed by Prof. James McCullagh.

IV.

216	7 17 25	Cross	883	Velocity 43·1 miles; train 49·5 tons; engine 14·5 tons; length 150 feet.
	17 38	Shaft gun.		
217	17 58	(5)	330	
	18 33	South gun.		
218	18 48	Cross lost	969	

V.

219	7 44 17	Cross	924	Velocity 28·3; train 53·5 tons; engine 14·5 tons; length of train 167 feet.
	44 39	Shaft gun, cross very strong.		
220	45 8	(5) brilliant. All the stars blue except the centre.	346	
221	45 27	(5) changes to cross ...	316	
	46 3	South gun.		
222	46 26	Cross lost	958	

VI.

223	8 1 9	Cross	965	Velocity 34·4 miles; train 114·5 tons; engine 21 tons; length of train 408 feet.
	1 30	Shaft gun.		
224	1 44	(5)	446	
225	2 12	(5) very strong	335	
	2 39	South gun.		
226	3 2	Cross lost	1029	

VII.

227	8 39 20	Cross	916	Velocity 45·6 miles; train 50·5 tons; engine 15 tons; train's length 152 feet. Newcastle Express.
	39 34	Shaft gun.		
228	39 55	(5)	313	
	40 26	South gun.		
229	40 47	Cross lost	1116	

Date.	Cross begins.	(5) begins.	(5) ends.	Cross ends.	Exit.	Train's velocity.	Train's weight.	
1847.	yards.	yards.	yards.	yards.		miles.	tons.	
Feb. 24	845	...	...	704	S.	11·0	77·5	
	699	...	...	780	S.	16·6	69·5	
	680	...	...	678	S.	13·8	58·5	
	...	...	...	834·5	S.	11·4	89·5	
Feb. 27	...	...	...	722	S.	15·4	54·0	
	736	...	...	915	S.	25·6	49·5	
	706	...	...	736	N.	17·6	270·5	
	736	319	...	1086	S.	31·7	112	
	727	322	...	cloud		18·7	51·5	
Mar. 11	802	...	...	cloud		17·7	147·5	
	cloud	...	...	921+	S.	33·0	122	
Mar. 12	822	303	...	766	N.	28·3	68	
	811	305	...	1074	S.	35·5	59·5	
	877	374	302+	1045	S.	30·9	124	Image much agitated at 1077 yards.
	855	302	416	1031	S.	37·7	50	
Mar. 15	1176	349	311+	1078+	S.	20·5	125·5	Train very long.
	775	303	324+	922	N.	22·6	209·5	
	1032	371	308+	992	S.	21·6	91·5	
	786	302	...	679	S.	14·8	49·5	
	1029	303	...	997	S.	33·0	106	
	854	...	...	782	S.	15·9		
	926	406	...	950	S.	23·7		
Mar. 16	1157	...	...	1157	S.	35·4	75	
	935	314	...	959	N.	24·8	67	
	915	352	308+	1110	S.	11·4	322	Train very long.
	870	...	...	878	N.	21·9		
	1038	...	...	988	S.	25·7	69·5	
	824	305	...	1079	S.	35·8	53·5	
	846	428	...	1058	S.	36·9	98·5	Long train.
	668	...	...	821	S.	20·1	55·75	
Mar. 17	1055	318	337+	1166	S.	33·9	104	Rather long.
	1076	315	...	1004	N.	28·7	70	
	828	...	...	892	N.	22·9	74·5	
Mar. 18	961	314	...	950	N.	27·3	87	Image oscillating.
	902	331	...	870	S.	30·4	78	
	992	313	...	1003	N.	25·6	63	
	824	303	343	1057	S.	31·6	72·5	
	705	...	...	830	N.	22·9	...	Light goods train.
	808	303	320	895	N.	18·2	84	Images confused.
	896	373	303+	1141	S.	29·7	62·3	Ditto ditto.
	1111	...	...	1115	S.	40·2	128	Long train.
	818	310	...	1076	S.	41·6	61·25	
Mar. 19	858	...	...	1128	S.	37·9	92·75	Observed by the Marquis of Blandford.
	919	306	...	978	N.	32·8	67	
	697	313	...	781	S.	32·1	68·5	Observed by Lord Alfred Churchill.
	1042	309	...	1005	N.	24·0	98·5	
Mar. 22	759	...	...	964	N.	23·6	86·5	
	1025	304	...	950	S.	20·7	68	
	827	312	...	972	S.	31·4	88	
Mar. 29	837	374	...	1057	N.	33·1	108	Long train.
	849	...	...	940	S.	33·4	67·5	Images confused.
	426	...	...	677	S.	20·8	48	Stopped at entrance.
	698	...	...	1018	S.	33·4	92·5	
	774	...	...	978	S.	39·5	55·5	Cloudy.
Mar. 30	771	314	...	899	S.	29	122	Observed by Professor James McCullagh.
	940	313	...	1014	N.	38·4	89·5	
	798	...	...	...	S.	29	pilot	
	883	330	...	969	S.	43·1	49·5	
	924	346	316	958	S.	28·3	53·5	
	965	446	335	1029	S.	34·4	114·5	Long and heavy engine.
	916	313	...	1116	S.	45·6	50·5	

That these results may be more easily appreciated, I have condensed the most important of them into the preceding Table, which gives in one view the distance at which that amount of disturbance begins and ends which produces the cross, that at which the far greater one occurs causing the appearance (5) (a system of three or more parallel rows) wherever it does appear, and the velocities and weights of the trains when known.

It is evident from this Table that the tremor which is sufficient to produce that disturbance of the mercury which shows a cross of stars is propagated to considerable distances—in one case to 1176 yards; and 24 per cent. of the entire are above 1000. Such distances do not pass the northern end of the tunnel, but go far beyond the southern. In the latter case the vibrations are excited while the train is in an open cutting; and those who suppose that the tunnel has much power in deadening them would of course expect that they would be sensible at a greater distance than at the other end. This does not seem, however, to be the case: and the Table shows that in this respect there is very little difference, if we take into account another cause of inequality, namely, that the tremor is manifested further at the exit than at the entrance of the train. The column headed "Exit" shows by s. that the exit was at the South end, and the entrance at the North.

Now, when the observations are examined where both were noted, we find that the limit of the cross is greater at the exit than at the entrance in 29 out of 39, or 74 per cent. of s., and 12 out of 16, or 75 per cent. of N. The reason of this, I suppose, is that the long-continued action of the train on the rails tends to produce a greater and more prolonged undulation in the mercury.

But the equal percentage shows that there is really no protecting power in the tunnel against the lateral propagation of tremors, whatever may be the case immediately above the crown.

In general one might expect trains to produce disturbance in proportion to their speed and their weight. To a certain degree this is true; but the exceptions are sufficient to show that other influences must be taken into consideration. Examples of high speed with comparatively small effect are afforded by the observations on March 18, II.; 19, III.; and 29, V.

Others of the reverse conditions are given by February 24, I., II.; March 18, VI.; and specially March 16, III., in which with a velocity of only 11·4 miles the cross was shown at 1110 yards. This it may be remarked is a decisive proof that any plan of protecting an observatory by slackening the speed of trains passing near it is entirely useless, even if it could be enforced.

It is probable that one cause of this high disturbing-power in slow trains is that already referred to, the long-continued accumulation of vibration, the quick ones passing beyond distance before the mercury has got into full vibration, the others having full time to do their work though with less intrinsic force. On this account also long trains are more disturbing than short.

The engine is not so paramount a disturber as might be expected,—the heaviest, and even a pair of them, not causing more tremor than occurs with the smaller ones.

In taking the cross of stars as the test of disturbance, I must observe that I do so, not because it is the earliest which appears, but because it marks distinctly an agitation greater than what is likely to occur at an observatory subject to ordinary perturbations. These produce in such a mercury-vessel as I used a single line of stars perpendicular to the length of the vessel. It should seem that then only one set of undulations fit to produce these images is excited in the mercury, the direction of which is regulated by the sides of the vessel *. The existence of the cross shows that a second set of waves perpendicular to the first has been developed : this always happens if the sides of the vessel are equal; and its occurring when they are so unequal as in the present case seems to indicate a corresponding excess of the power which causes them. If the agitation be still greater, it seems as if each of the images which form the cross became the origin of a row of secondary images, the result of which is the form (5), a series of parallel rows of stars varying from two to ten, or even filling the whole field. This token of ultra disturbance is confined between lines making angles of 45° with the perpendicular to the rails—in other words, to distances under 427 yards, and when the train is nearly in the centre of the tunnel. It is (except in two instances) only seen when the cross is visible beyond 1000 yards: when the agitation is still further increased the images vibrate in every direction, and with yet more of it the whole becomes a mass of nebulous light; of both which some examples may be found in these observations.

The opinion maintained by the late Mr. Robert Stephenson, that much of these railway tremors were due to the sound of the train, although not probable, induced me to try some experiments by firing cannon, maroons, and rockets at various distances.

One of these cannons (for I had two, each $\frac{3}{4}$ of a pound calibre) heavily loaded, at 300 yards produced (5), cross, and line simultaneously with my hearing the reports; but all disturbance was over in about 1·5 second. At 2020 yards there was the cross synchronous with the report, and of the same momentary character; and even at 3000 yards the cross could be traced. This seems to have been due to the momentary impulse of the sound-wave, for the continuous roar of two-pound rockets fired at 82 feet from the mercury, though very loud, disturbed it very little; while the explosions of eight ounces of powder in their heads about 800 yards above the ground produced all, the (5), cross, and line. A still more interesting experiment was, firing the cannon in the tunnel at the point where the perpendicular from the observatory met it. In this case two disturbances were seen—one propagated through the ground, the other through the air with about a second of time interval. The sound probably made its way chiefly

* For details on this I may refer to my Report to the Admiralty, published by order of the House of Commons, July 6, 1846.

through the shafts; but even had they been closed, it seems unquestionable that the report, and of course the sound of a train, would travel through the earth *.

I should have prosecuted these researches further, especially in reference to the velocity with which these tremors are propagated through the ground, but that Lord Auckland's letter to me led me to hope that all danger to the Royal Observatory was past, never to return. I therefore contented myself with reducing the observations I had made. As, however, the Railway Moloch seems never likely to be satiated with victims, and as the observatories of Oxford, Armagh, and again that of Greenwich have been marked for sacrifice, it seems to me a duty to place before the public the facts which had been collected at a great expense of labour, and some pecuniary outlay.

They were made without any bias, or any motive but a desire to ascertain the actual truth; and in addition to their bearing on practical astronomy, I hope that they may not be without use in reference to some other departments of science.

January 7, 1864.

Dr. W. A. MILLER, Treasurer and Vice-President, in the Chair.

The following communications were read:—

I. "Extract of a letter to General Sabine from Dr. Otto Torell, dated from Copenhagen, Dec. 12, 1863." Received December 18, 1863.

The Swedish Diet has given the necessary money to complete the survey for the measurement of an Arc of the Meridian at Spitzbergen.

When the proposal was submitted to the Diet by our Government, at the instance of the Academy of Sciences at Stockholm, it was passed without opposition in the three first houses of the Diet (viz. the Nobles, the Clergy, and the Burghers). In the fourth house (the Peasants), only one Member opposed the proposal, on the ground of the high amount of the Budget. He was replied to by seven or eight other Members, advising that the house should not oppose a grant which had for its object to advance science. In

* An interesting fact was observed with the maroons. They were fired vertically from a mortar twenty feet from the observatory, and had fuses which gave them flight for six seconds. The mercury showed the usual intense disturbance when the mortar was fired, and also at the explosion of the maroons in the air. But there was also an intermediate disturbance which I cannot explain but by supposing it to be as it were an echo of the earth-wave caused by the discharge of the mortar and reflected from *the masonry of the tunnel*. I showed it to the Marquis of Blandford, to Lord Alfred Churchill, and to Professor James McCullagh; unfortunately the nights Dr. Robinson and Mr. Warburton accompanied me to Watford, not a single star was visible. On repeating the experiments at Campden Hill, nothing of the sort occurred.